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PLASMOID COLLISIONS IN AN AXIALLY SYMMETRIC MAGNETIC FIELD

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ABSTRACT: Plasmoid collisions were investigated in axially symmetric magnetic fields using the principle of counter injection into the trap and measuring the emission resulting from the collisions. A strong interaction was found at high strengths of the magnetic field.

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The study of the interaction of counter-streaming plasma bunches (plasmoid streams) is of interest in connection with the problem of injecting plasma into a magnetic trap. /71*

As shown by numerous experiments, one of the difficulties in filling the trap with plasma bunches lies in the fact that bunches having relatively large translational energy penetrate into the trap easily and also leave it easily. This applies to both the mirror traps and traps with cusp-type geometry. It is conceivable that one of the methods of surmounting this difficulty is the injection of counter streams into the trap under the conditions of their interaction.

As is well known the interaction of counter plasma streams can be caused by two mechanisms: in a relatively dense and cold plasma - by Coulomb collisions and in a rarefied and hot plasma - by collective interactions. As a result of such interactions the kinetic energy of the plasma streams can be transformed into thermal energy.

Plasmoid collisions were experimentally investigated in [1 - 3]. In [1] an attempt was made to detect the "two-stream" non-Coulomb interaction in counter streaming bunches along a homogeneous axial magnetic field; deuterium bunches created by titanium absorptive sources had the following parameters: energy of the directed motion ~ 900 eV; temperature of the ions ~ 45 eV; temperature of the electrons roughly the same as that of ions. The interaction was not detected since the electron temperature of the colliding bunches was not sufficiently high. Similar experiments have been described in [2] but these experiments were conducted using coaxial plasma injectors. Each injector produced two successive bunches, the first bunch was faster but less dense than the second. It was found that the faster bunches /72
do not interact (also because of small electron temperature) but Coulomb interaction of the second, i.e., of the slower bunches was noticed. Although in this work the attention was devoted mainly to the study of the first bunches, it was suggested that the second bunches could prove to be more suitable for use in thermonuclear devices since they are efficiently captured in the trap and can be subsequently heated, for example, by adiabatic compression. Finally in [3], conditions for filling a trap of cusped angled geometry by a simultaneousinjection of plasmoids (plasma bunches) through annular and axial slits were investigated. Coulomb interaction and the capture of the plasma in the trap were observed. Although the confinement of the plasma in the trap was apparently determined mainly by the large pressure of the neutral gas (from the "tail" of the plasma streams), nevertheless, with the counter injection the time of confinement was several times larger than with the injection of single plasmoids.

The object of our work is to investigate the interaction of counter-streaming plasmas in an axial field, under experimental conditions similar to those described in [2] (for the second plasmoids).

*Numbers in the margin indicate pagination in the foreign text.

Experimental arrangement and methods of measurements.

The experimental arrangement is shown schematically in Fig. 1. The plasma bunches were produced by conical induction injectors 1 [4]. The bunches injected from the sources were first made to propagate in glass tubes 2 (diameter 9 cm, length 25 cm) and then in vacuum chambers 3, made of transparent plastic (18 cm I. D., length 100 cm). The plasmoid collision occurred in the central vacuum chamber 6 (a glass tube 11 cm in diameter and 37 cm long). The guiding magnetic field was produced by two long 4 and two short 5 coils. Figure 2 shows the distribution of the magnetic field along the system in which the field has a mirror geometry with a mirror ratio of ~ 2.3. As seen from Figs. 1 and 2, the system is symmetric with reference to the interaction chamber except for the stainless steel chamber 7 (Fig. 1) through which the evacuation was affected. The evacuation was done by an oil diffusion pump. On freezing out the oil vapors by liquid nitrogen the residual gas pressure in the system was ~ 10^{-6} mm Hg.

Each injector was fed from a separate condenser battery (capacity 27 μ F), but /73
these batteries were charged and actuated simultaneously. The operating regime of each of these injectors could be somewhat regulated due to the independent system of admitting the gas into the injectors. The voltage on the valves, the pressure under the valve caps and the time of admitting the gas could be changed independently. Furthermore it was possible to operate with a single injector (without admitting gas into the other). Ordinarily the operating regime was the following: voltage on the batteries - 30 kV, amount of gas admitted - 3 cm^3 (at normal pressure), time lag between actuating the valve batteries and the source batteries - 270 μ sec. As shown by preliminary measurements, [4, 5], in this regime the bunches had a velocity of ~ 1.10^7 cm/sec and an initial charged particle density (in the region near the injectors) of 10^{15} cm^{-3}; the heavy impurities comprised about 10%.

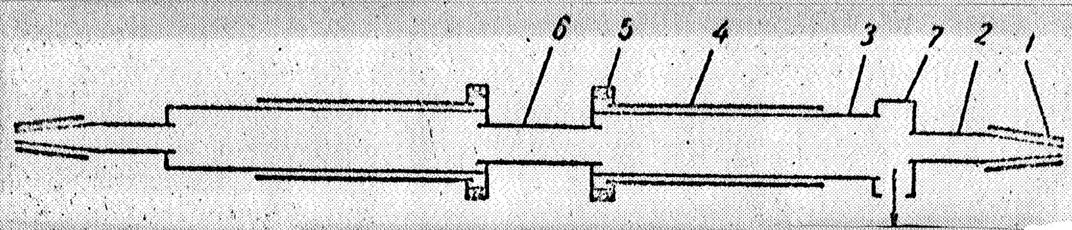

Figure 1. A Schematic Diagram of the Experimental Arrangement: 1) conical induction injector; 2) glass tube; 3) transparent plastic chamber; 4) long coil; 5) short coil; 6) central chamber; 7) evacuating chamber.

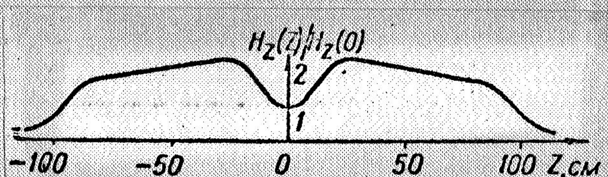

Figure 2. Axial Dependence of the Component H(z) of the Magnetic Field Along the Axis of the System.

A condenser battery with a capacity of 3000 μ F was discharged into the coils for producing the magnetic field; the discharge period was 30 m sec. The injectors were actuated 7.5 m. sec after actuating the field batteries so that during the entire period of the motion and the interaction of the plasmoids the field was nearly constant and at its maximum value.

The field could attain a maximum value of 2 kOe in the central plane of the system and hence 4.7 kOe at the mirrors.

The plasma parameters and their variation as a function of the magnitude of the magnetic field were determined in the central plane of the system, i.e., in the region of the collision of the bunches. The measurements were carried out by a magnetic probe and by spectrograph ISP-51.

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The magnetic probe consisted of a single coil passing around the glass tube 6 (Fig. 1) in the central plane, i.e., in the region of quasi-homogeneous field. The slow variation of the vacuum magnetic field made it possible to do without compensating the probe for this field. As well known, such a probe records the change in the magnetic field caused by the induced currents in the bunches as well as by the thermal diamagnetism of the plasma. There is some basis to assume that under the conditions of our experiments the bunches become magnetized by the time they interact and the induced currents in the region of interaction are unimportant. Therefore the probe records only the thermal diamagnetism. In these conditions the linear density of the transverse energy of the plasma can be determined directly from the magnitude of the probe signal V_p:

$$\pi r^2 nk (T_e + T_i) = \frac{10^8 RCH_0}{4\pi} V_p$$

where r, n, T_e and T_i are respectively the radius, the density and the electron and ion temperatures of the plasma; k is the Boltzman constant; H_0 is the intensity of the vacuum magnetic field; RC is the time constant of the integrator.

The time variation of the intensity of individual spectral lines and of the continuous emission from the plasma was recorded with the spectrograph and photographic attachments. A long focus camera was used so that the dispersion of the instrument in the region of H_β lines was ~ 7 Å/mm. Furthermore the time integral spectrum was photographed with a short focus camera (dispersion ~ 43 Å / mm). Because of the weak luminosity of the plasma the photographs were made on the film RF-3 and the lines were photometered on the microphotometer MF-4.

Results of the measurements and discussion

*Figure 3 shows typical oscillograms of the magnetic and the corresponding light signals at different magnetic field intensities (for the upper row of the oscillograms $H_0 = 0$, for the middle row $H_0 = 0.9$ kOe, for the bottom row $H_0 = 1.8$ kOe). The first column contains the magnetic signal (upper oscillograms) and the continuum emission (lower oscillograms) for a single injector operation. The second column gives the same oscillograms for two injector operations (signals were obtained with the same amplification). The third column corresponds to the same conditions as the second; only in place of continuum emission the H_β line is given (the magnetic signals in the second and the third columns were obtained under identical conditions so that they represent the reproducibility of the measurements). /75

*Figure not reproducible.

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Figure 3. Typical Oscillograms of the Signals:

CODE: a) Magnetic Signals and Continuous Emission ($\lambda = 4830$ Å) of One Bunch; b) Magnetic Signals and Continuum Emission of Two Plasmoids; c) Magnetic Signals and Hydrogen Emission (H_β line) of Two Bunches.

From these and other similar oscillograms it is seen that all the light signals (including the emission from the impurity lines CII/4267 Å and OII/4652 Å)[1] have the same character; their maximum corresponds to a later instant of time than the maximum of the magnetic signal. The relatively weak emission from the leading part of the bunch indicates a high degree of ionization and purity of the plasma; the neutral particles and the heavy impurities move with smaller velocity and lag behind the front part

The intensity of the continuum emission is approximately constant over the entire visible region of the spectrum and is approximately 50 times smaller than the intensity of the H_β line. This emission is apparently a sum of the recombination and bremsstrahlung emissions.

The dependence of the transverse energy on the magnetic field H_0 was determined /76
from the maxima of the magnetic signals (Fig. 4)[2]. As seen from Fig. 4, with a single injector operation there is no significant change in the transverse energy

[1] In the integral spectrum only these impurity lines are visible. As shown in [4, 5], carbon and oxygen are formed as a result of the decomposition of the oil from the diffusion pump and enter into the plasma at the time of the discharge as well as from the walls of the plasma duct during the motion of the plasmoid.

[2] Curve 1 in Fig. 4 is the mean of the results for each injector; this averaging gives an error which does not exceed 10%.

density with the increase in the magnetic field. Some increase observed for weak magnetic fields (upto $H_0 \simeq 1.0$ kOe) is apparently accounted for by the reduced plasma loss during the motion of the bunch in the guiding magnetic field. For stronger fields ($H_0 > 1.5$ kOe) a subsequent decrease in the energy density is possibly caused by the partial reflection of the plasma at the entrance into the guiding magnetic field. With the combined operation of the two injectors the energy density at $H_0 \simeq 1$ kOe is roughly equal to the sum of the energies of each bunch. This indicates that plasmoids move through one another freely without interacting. However, with further increase in the field the energy density continues to increase in spite of the decrease of the energy of each injector in separate operation. At $H_0 \approx 2$ kOe the energy density attains a value of 5.10^6 erg/cm (this exceeds the corresponding value for a single bunch by roughly a factor of 10). The duration of the signal also increases by a factor of 2 - 3.

Obviously such a nonadditive increase in the energy indicates a strong interaction of the bunches. Under the conditions of our experiments it is unlikely that this was a "collisionless" interaction. It is most probable that the interaction of the bunches was caused by Coulomb collisions between the particles. Actually, on the basis of previous measurements [5] it can be assumed that under the conditions of the present experiments the density of the charged particles in the bunches prior to their interaction was $\sim 10^{14}$ cm^{-3} and the temperature was ~ 10 eV. For these conditions the time /77
between ion-ion collisions is $\sim 10^{-7}$ sec; for the bunch velocity of $\sim 1.10^7$ cm/sec the length of the Coulomb deceleration determined by this time is ~ 1 cm.

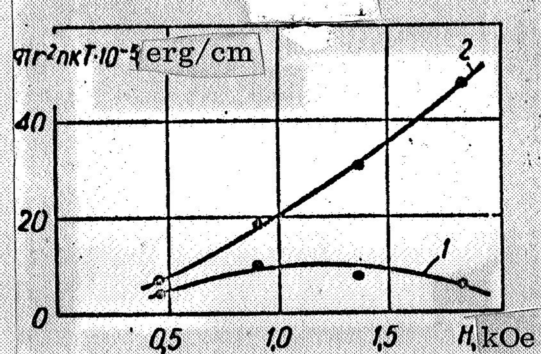

Figure 4. Dependence of the Linear Transverse Energy Density of the Plasma on the Magnetic Field:

1—One bunch; 2—two bunches.

The results of the optical measurements are illustrated by Figs. 5 - 7. Fig. 5 shows the change in the intensities of the continuum emission and the OII impurity line as a function of the magnetic field. Assuming that the intensity of the continuum emission J is the sum of the recombination and the bremsstrahlung radiations and hence is proportional to the square of the density of the charged particles, the corresponding dependence for the quantity $J^{1/2} \sim n$ was constructed from Curves 1 and 2 of Fig. 5. This dependence is shown in Fig. 6. (These measurements were carried out for the maximum light signals so that they correspond to some middle part of the bunch; due to the lack of a sufficiently good reproducibility of the shape of the light signals, it was not possible to carry out similar measurements for the leading part of the plasmoids). The dependence of the halfwidth of the H_β line on the magnetic field, obtained from the integral spectrum is shown in Fig. 7. $\Delta\lambda$ is the difference between the experimental halfwidth and the halfwidth of the instrument contour[1].

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[1] The determination of the plasma parameters from the halfwidth of the H_β line is difficult since under the conditions of our experiments the widening is caused by Stark effect as well as by Doppler effect.

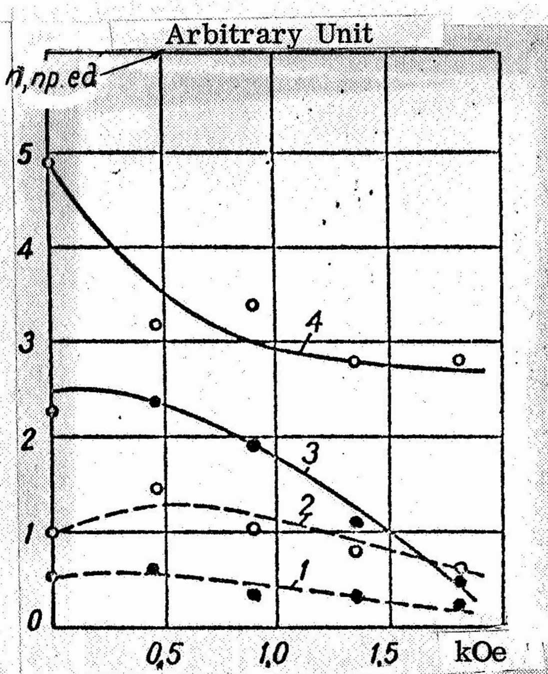

Figure 5. Dependence of the Intensities of the Continuum Emission and Oxygen Emission on the Magnetic Field:

1—Continuum emission (λ = 4830 Å) of one bunch; 2—continuum emission of two bunches; 3—oxygen emission (λ = 4652 Å), one bunch; 4—oxygen emission, two bunches.

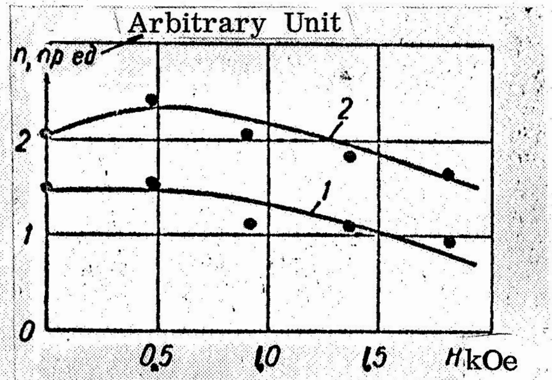

Figure 6. Dependence of the Density of Charged Particles on the Magnetic Field:

1—One bunch; 2—two bunches.

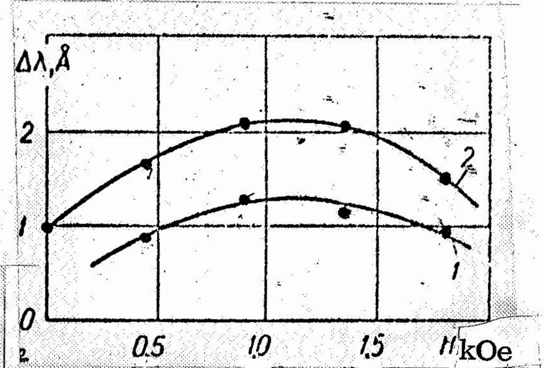

Figure 7. Dependence of the Half-width of the H_β line on the Magnetic Field:
1—One bunch; 2—two bunches.

As seen from Figs. 5 and 6, the intensity of the continuum emission and more so the dependence characterizing the density, have a weak dependence on the magnetic field and do not indicate an increase in the density when the field is increased. The intensity of the emission for two bunches exceeds that for a single bunch by approximately a factor of 2. The dependence of the halfwidth of the H_β line on the magnetic field is qualitatively similar (Fig. 7). For the intensity of the OII impurity lines the observed dependence is somewhat different. In the case of a single bunch OII intensity decreases with the increase in the magnetic field, which indicates a reduction in the impurities entering into the plasma from the walls of the plasma duct (as a result of the radial compression of the bunch). A decrease in the intensity of the impurities emission is also observed in the case of counter streaming bunches in weak fields ($H_0 \approx 1$ kOe); however, in large fields the intensity of this /78
emission remains unchanged.

Thus in the case of single beams the results of the optical measurements qualitatively agree with those of the magnetic measurements, even though the reason for some decrease in the energy density and in the density of the particles on increasing the field is not conclusively determined (we shall remark that a similar decrease in the density of the particles on increasing the field was observed by the authors of work [2] for fast plasmoids).

In the case of interacting bunches the magnetic and optical measurements may appear to be inconsistent since an increase in the energy density is accompanied by a decrease in the density of the particles. Possibly this is explained by the fact that in the interaction the bunches get stopped and expand radially; as a result the change in the density of the particles is insignificant. The behavior of the intensity of the impurity lines can be explained by the fact that as a result of the expansion the plasma comes in contact with the walls of the chamber. Thus the increase in the transverse energy recorded by the magnetic probe is apparently caused mainly by the increase in the plasma temperature (primarily ion temperature), which occurs due to the thermalization of the initial kinetic energy of the bunches. Actually, if it is assumed that as a result of the interaction the plasma fills the glass tube, i.e., $r \simeq 5$ cm and the density remains $\sim 10^{14}$ cm^{-3}, then it follows from the equality /79 $\pi r^2 nkT = 5.10^6$ erg/cm that $T \sim 100$ eV, which is of the same order as the initial kinetic energy of the bunches. Again, the half width of the H_β line, determined from the integral spectrum does not conform to such a high temperature. This may be accounted for by the fact that the hot plasma remains in the trap only for a short time; this is also indicated by the short duration of the magnetic signal. Comparatively rapid decrease in the energy density of the trapped plasma is apparently caused not so much by the escape of the plasma through the loss come as by its cooling due to the arrival of colder and weakly ionized "tail" of the bunch in the interaction region.

In conclusion we shall mention that the results obtained here must be considered as preliminary. This is especially true for the optical measurements which characterize not the leading but some middle part of the bunches. Thus for the verification of these results of interaction, it is necessary to measure the radius, the particle density and the temperature in the leading part of the interacting plasmoids.

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